

KD6040

Individual Physics Project

FINAL REPORT

BSc (Hons) Physics

MPhys (Hons) Physics

BSc (Hons) Physics with Astrophysics

MPhys (Hons) Physics with Astrophysics

2020/2021

The Formation and Evolution of Blue Super Giant Stars (BSGs)

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12/05/2021

Declaration

I hereby declare that the work contained in this document is all my own work. I also confirm that when this work uses ideas and opinions from the work of others, these are credited in full by citing the corresponding references.

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# ABSTRACT

This project studies the fundamental, defining properties of Blue Supergiant stars (BSGs) as well as important processes that occur within and as a consequence of BSGs. As early spectral O and B type stars that were present in the early universe, these stars host several important processes that can determine the evolution of the galaxies and even the universe. BSGs are ideal candidates for determining extragalactic distances [50] because they are the brightest stars in their galaxies in terms of optical light.

BSGs form through a four-step process of compression, collapse, accretion and disruption which is a much faster process and differs significantly from stellar mass star formation. BSGs begin hydrogen burning after a few 100,000 years. They then enter the main sequence phase yet continue to accrete mass whereas smaller mass stars will accrete a mass equivalent to their final mass before entering the main sequence which can take millions of years for such stars.

During their lifetimes, BSGs experience many forces, one of the most notable being radiative pressure which causes stellar winds and mass loss as a consequence. Measurements from external sources have been researched as well as equations being tested to determine whether this mass loss is significant. If the average mass loss rate of around 1 Mʘ, the mass of the Sun, every million years stays constant for the lifetime of a BSG then around 10 Mʘ would be lost in the star’s lifetime. However, there is no evidence to prove that mass loss remains constant or that it lasts for the entirety of the star’s lifetime. Therefore, mass loss from BSGs is not very significant.

Studies have been researched to determine the magnetic properties of BSGs such as if BSGs can host magnetic fields. The MiMeS [28] and BOB [5] surveys have been studied and conclusions show that a small fraction of O and B type stars can host detectable fields. The theories of stellar spots and stellar flares in BSGs were also studied to determine if these processes both could occur and how they compare to a cooler, smaller star like the Sun. It was found that a small fraction of a survey of stars were found to host detectable fields and that it could be possible for B type stars to experience stellar spots if they have a thin convective envelope below their surface.

BSGs live very short lives, on average around ten million years, when compared to other stars. Their evolutionary path leads through one of the most energetic phenomena known, a supernova, then down one of two paths as either a black hole or a neutron stars. The deaths of massive stars shape the evolution of galaxies and the next generation of stars which shapes the evolution of the expanding, evolving universe.

# INTRODUCTION (General introduction to BSGs)

## **Properties of BSGs**

Stars are vital celestial bodies that have led to the evolution of the universe through its lifetime of around 13.7 billion years. Some stars can support life on orbiting planets such as the Sun, whereas other stars can create the materials necessary for the formation of planets and the evolution of galaxies and the universe. Such stars are known as high-mass or early type stars and such an example of this are blue supergiant stars (BSGs). Stars are classified by several methods; the most common way is by spectral class. This method considers a star’s temperature when classifying it into one of the spectral classes: O, B, A, F, G, K and M, with O type being the hottest class and M type being the coldest class [1]. For the specific case of main sequence stars, there is a general corelation of increasing luminosity and mass from M type to O type stars.

As a result, the majority of BSGs are classified as O type and a selection are classified as B type stars. As a consequence of such high temperatures, BSGs have vast amount of energy available for fuel burning therefore they consume fuel at an extraordinarily fast rate. They consume fuel so fast that these stars only live for 10 million years or so, as opposed to the Sun which is currently around 4.5x109 years old and will continue to exist for a similar amount of time, subsequently BSGs live fast and die very young for stars. Some examples of BSGs are given in table 1 along with their masses, temperatures, and other properties. It is theorized that these early type stars provided light in the form of high energy photons that ionized the neutral hydrogen that the majority of the early universe was composed of. This is known as the epoch of reionization and occurred several hundred million years after the Big Bang [2]

Table 1: Basic property data for a sample collection of BSGs

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Star Name | Star Mass (Mʘ) | Star temperature (K) | Star Luminosity (Lʘ) | Star radius (Rʘ) | Spectral class |
| Naos - Zeta Puppis [3] | 56.1 | 40,000 | 813,000 | 14 - 26 | O4 If(n)p |
| Alnitak Aa [4] | 33 | 29,500 | 250,000 | 20 | O9.5 Iab |
| Alnitak Ab [4] | 14 | 29,000 | 32,000 | 7.3 | B1 IV |
| Alnilam [5] | 40 | 27,500 | 537,000 | 32.4 | B0 Ia |
| Saiph [6] | 15.5 | 26,500 | 56,881 | 22.2 | B0.5 Ia |
| Omicron2 Canis Majoris [7] | 21.4 | 15,500 | 220,000 | 65 | B3 Ia |
| Aludra [8] | 19.19 | 15,000 | 105,442 | 56.3 | B5 Ia |
| Rigel A [9] | 21 | 12,100 | 120,000 | 78.9 | B8 Ia |

BSGs being classified as either O type or B type signifies that they have minimum average surface temperature values of 11,000 K, minimum average solar radii of 14 Rʘ, where 1 Rʘ indicates the radius of the Sun which is 6.960x105 Km, average masses of around 30 Mʘ, where 1 Mʘ­ is 1.98x1030 Kg, and luminosities of around 20,000 Lʘ and above, where 1 Lʘ is 3.84x1026 W [10]. The sun is classed as a G type star based on its surface temperature of 6000K, its yellowish colour, and its relatively low luminosity value.

Another classification scheme used to differentiate stars is via their luminosity or total brightness, this is known as the Yerkes luminosity class and uses roman numerals in which I indicates the most luminous supergiant stars and VII indicates the dimmest white dwarf stars. BSGs are most often classified as class I due to their extraordinary high luminosity values and often class I is spilt into Ia and Ib to differentiate between luminous supergiants and exceptionally luminous supergiants. The stars in this table generally increase in temperature and luminosity as the luminosity class increases from VII to Ia. The spectral class column in table 1 shows first which spectral type each star is, it also shows a number next to the spectral class. This is a subdivision of each spectral class which adds another level of classification. This subdivision goes from 0 to 9, where 0 represents hotter and 9 represents colder. For example, O9 is a hotter classification than B0. There are other letters in spectral classification which each represent different characteristics. From table 1 it is shown that Naos has a spectral class containing both an n and a p term. The n term represents broad absorption lines due to fast rotation and the p term represents a strong absorption line of metals [3].

Possibly the most used and well-known diagram in the field of astrophysics is known as the Hertzsprung-Russell diagram, which plots luminosity against temperature and is used to visualise the spectral classes of stars. Figure 1 shows a variant of the Hertzsprung-Russell diagram that has an additional plot of absolute magnitude with added luminosity classification lines. Absolute magnitude is the measure of how bright a star is if it were located 10 Parsecs away. Due to the axes of the diagram, BSGs are found at the top left of the diagram corresponding to temperatures >10000K and luminosities >20000Lʘ.

Properties such as mass, luminosity and distance can be calculated using observations from Earth. Distances from Earth to nearby stars can be calculated whilst utilising a phenomena known as stellar parallax. This process involves observing the position of a star and then 6 months later, which corresponds to half of the Earth’s orbit around the Sun, observing the same star and measuring the apparent change in position of the star with respect to the background stars which are assumed to be fixed in position. This observation will yield an angle in arcseconds which can then be plugged into the equation:

(1)

Where:

* d is distance [parsecs] (1 parsec corresponds to 3.086x1016 m)
* is the measured parallax of the observed star [arcseconds] (206265 arcseconds corresponds to 1 radian)

Therefore, knowing the apparent change in position of a star in arcseconds allows the distance to be calculated in parsecs and then converted into km, or any other unit of distance. This method could work for any star which has a measurable parallax. From the apparent brightness of a star, which is also known as the flux, one can deduce the luminosity of the star via the equation [11]:

(2)

Where:

* L is luminosity [W] (But is often measured in Lʘ for stars with higher luminosity values)
* d is the distance to the star from the Earth [m]
* F is the flux of the star [W m-2]

So, knowing the flux and radius of a star allows the luminosity to be calculated which in turn leads to the temperature being able to be calculated. This is how some physical properties of stars are calculated.

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Description automatically generated

Figure 1: The Hertzsprung-Russell diagram shows the classification of different star types based on luminosity and surface temperature [12]. BSG are located around the top left of the diagram whereas the sun is located around the centre of this diagram.

## **Formation of BSGs**

The most common and widely accepted theory about star formation is that they form in large molecular clouds known as nebulae. These clouds are composed of gases, dust, and large densities of hydrogen particles. Over a large period of time, gravitational forces, or in some cases a dust cloud collapse caused by external forces, cause a single dense point to form, and collect gas, particles, and mass. Friction in this dense point causes heat to be generated, pressure to increase and eventually light to be emitted and thus either a solar nebula or a protostar forms. Conservation of angular momentum causes spin which can flatten out the star or lead to the creation of an accretion disk. Eventually enough heat is generated for the hydrogen to begin fusing into helium and the star is “born”. It is thought that this is a general process of star formation for stars of stellar mass, such as the Sun, and high mass stars of masses >8Mʘ. The main difference could be the density of hydrogen within the nebula, which is thought to be around 1024 atoms cm-2 for nebula of high mass stars which is much denser than a nebula that forms a stellar mass star similar to the Sun [13], this difference will be discussed later in section 3.1.

A generalised 4 step process can be used to explain the formation of massive stars with step one being the compression phase. This phase initiates the entire formation process by forming cold, dense molecular cores, and supersonic turbulence produces compressed pockets of gas that remain gravitationally bound and lead onto the next phase which is the collapse phase. In this phase gravity becomes the dominant force as it overcomes pressure forces, magnetic forces, rotation, etc. and causes the gas to collapse nonhomogeneously i.e., the densest parts collapse the fastest in the system. During collapse, the gas heats up, gas pressure increases considerably and due to the conservation of angular momentum, rotational forces increase which can lead to accretion disks.

This leads onto the third step which is the accretion phase. In which the protostar begins its evolution towards the main sequence phase, hydrogen fusion eventually begins, and stellar winds will develop due to strong radiative pressure in high mass star formation. The final fourth stage is the disruption phase where the nebula gets disrupted due to the influence of high mass stars as they are born due to gravity, stellar winds, and radiation forces [13].

## **Processes of BSGs**

### **1.3.1 Fusion**

All stars produce energy and heat through a process known as nuclear fusion. G type stars such as the Sun fuse hydrogen atoms, known as protons, into helium atoms, known as alpha particles through proton-proton fusion chains of which there are multiple types that the hydrogen in the sun undergoes to some extent that is dictated by probability. On the other hand, high mass stars undergo a different fusion process known as the CNO cycle which still involves hydrogen fusing into helium but by a different reaction chain.

Due to BSGs having much higher interior temperatures, more energy is available for fusion and therefore heavier elements can be created within the star. This cycle involves hydrogen reacting with carbon, nitrogen, and oxygen over several reactions to create helium with the release of energy, around 25MeV. This is a catalytic reaction meaning that there is not net change in carbon, nitrogen, or oxygen densities for the main sequence phase as they are generated in a later step in the cycle. It is in this main sequence phase where the majority of the hydrogen burning occurs and once hydrogen fuel becomes scarce, the star will look to heavier elements to fuse as it moves off the main sequence. The main nuclear fusion reaction in the Sun, the proton-proton 1 reaction, generates around 26.7MeV [14]. Much like proton-proton fusion, the CNO cycle has variations up to 4 variations which are CNO-I, CNO-II, CNO-III and CNO-IV, and much like fusion in the Sun these variations have slightly different reactions with varying probabilities of occurring. The primary CNO cycle is shown below with the energy generation at each step:

126C +11H 137N 1.95 MeV

137N 136C +e+ + 1.2 MeV

136C + 11H 147N + 7.54 MeV

147N + 11H 158O + 7.35 MeV (3)

158­O 157N +e++ 1.73 MeV

157N + 11H 126C + 42He 4.96 MeV

Total 24.73 MeV

### **1.3.2 Stellar winds**

The CNO cycle likely contributes a majority of the vast amounts of radiation in BSGs as well as radiative pressure which is a strong characteristic of cores in BSG and has further consequences in the form of strong stellar winds. This is a phenomenon of a continuous flow of material out of the star resulting from the radiative pressure within the star [15]. Stellar winds can range from a few hundred km s-1 to thousands of km s-1, table 2 shows some of the stars from table 1 but with measured stellar wind values that could be found. As a consequence of stellar winds ejecting material such as gas, dust, and particles, out of the star, it will experience a reduction of mass which is measured in Mʘ yr-1 due to the stars losing significant amount of masses over long periods of time when compared to the mass of the sun. Table 3 shows observed mass loss values for the example stars shown in table 1. Mass loss is hypothesized to be relative to stellar wind speeds meaning that faster stellar wind speeds could result in more mass being lost, this hypothesis will be discussed in section 3.3. Stellar winds in massive stars can be observed through their spectral line shape which is distinctive an­­d known as the P Cygni profile.

BSGs often have strong Ultra-violet (UV) spectra due to their high temperatures and higher energy levels being available. This makes the UV part of their spectra being the easiest to detect using spectroscopic methods. The P Cygni profile is thought of as a combination of features across the star’s spectra, where the majority comes from the UV part. A further explanation and diagram of a P Cygni profile is shown in section 3.3. There are two main characteristics observable in the P Cygni profile [18]:

1. When the star’s stellar wind absorbs some of the radiation emitted by the star and moves towards the observer on Earth, this is known as blue-shifted absorption dip. Blue shift occurs when an observed object moves towards the observer, the opposite phenomena, red shift, occurs when an observed object moves away from the observer. An example of a red shifted object is a galaxy that appears to move away from the Earth due to the expansion of the universe
2. When photons absorbed from the star’s radiation in the stellar wind scatter light particles towards the observer on Earth or when photons are directly emitted by the stellar wind then this is known as red wing emission

Therefore, observing the spectra of a BSG via its spectral lines in the UV spectra could allow calculations of stellar wind speed and mass loss rates.

Table 2: Measured stellar wind velocities of the sample collection of BSGs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Star Name** | **Star Mass (solar mass)** | **Star temperature (K)** | **Star Luminosity (Solar luminosity)** | **Stellar wind velocity (km s-1)** |
| Naos - Zeta Puppis | 56.1 | 40,000 | 813,000 | 2250 [3] |
| Alnitak Aa | 33 | 29,500 | 250,000 | 2000 [16] |
| Alnilam | 40 | 27,500 | 537,000 | 2000 [5] |
| Aludra | 19.19 | 15,000 | 105,442 | 500 [17] |
| Rigel A | 21 | 12,100 | 120,000 | 230 [9] |

### **1.3.3 Binary systems**

Binary star systems occur when there is a pair of two close stars orbiting each other. This often occurs with a primary star of greater mass, potentially a BSG, and a secondary star of lesser mass, potentially a neutron star or white dwarf star [22]. Various studies have been carried out and will be discussed in section 3.4. Gravitational forces play a key role in mass loss in binary systems as mass can be transferred between the two stars if one has a stronger gravity and if the stars grow to encompass the Roche-lobe. The Roche-lobe is a region around a binary system and any material within this region is gravitationally bound to the star [23]. If material moves out of this region, then it is no longer gravitationally bound and therefore can be transferred to the other star in the binary system. Stars can expand to fill the Roche-lobe and therefore can cause some of its material to be transferred between the primary and secondary star. Figure 2 shows a diagram of a Roche-lobe in a binary system. If angular momentum of the system were to decrease, then the orbit of the secondary star would shrink and conversely cause the Roche-lobe to shrink and cause a period of time where mass transfer is possible between the two stars in the system.

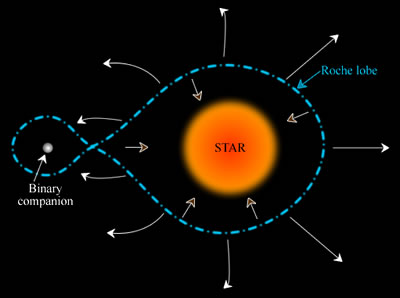


Figure 2: A Roche-lobe diagram between a binary star and its companion star [24]

### **1.3.4 Magnetism**

Stars experience magnetic phenomena which result from interactions with their magnetic fields. The Sun experiences phenomena such as Sunspots which are areas on the Sun’s surface known as active regions and have very strong magnetic fields of between 1 KiloGauss and 3 KiloGauss [26]. For comparison, the average magnetic field strength for the sun is around 1 Gauss [26]. The Sun has a convective zone near its surface where convective transport dominates over radiative transport, as a consequence other phenomena, such as solar flares, can occur when there are disturbances in active regions which cause energetic eruptions that can last for 100’s to 1000’s of seconds and sometimes are accompanied by a coronal mass ejection (CME). CMEs are ejections of mass and plasma out of the solar corona. This plasma travels at great speeds and can interact with the Earth’s magnetic field which leads to the generation of the northern and southern lights [27].

From a study of magnetism in massive stars (MiMeS) (Wade et al., 2013) [28] it was found that there is evidence to support the possibility of O type and B type stars having magnetic fields. For those observed with magnetic fields, it was found that they ranged from a few hundred Gauss to several thousand Gauss. There was no clear correlation found between properties such as age, mass or rotational velocity and magnetic field strength. This study as well as another study known as B-field in OB stars (BOB) will be studied and analysed in section 3.

## **Evolution and Death**

BSGs burn fuel as at extraordinarily fast rate, and as a consequence they quickly reach the late stages of their life. They quickly use up their hydrogen fuel in the CNO cycle and so move off the main sequence phase and on to post main sequence phases. In these phases the BSG must fuse heavier elements as nuclear fuel starting with the fusion of helium into carbon which is the process known as the triple alpha process. Carbon fusion then takes place then neon and silicon fusion until iron fusion is reached. Iron, with a chemical symbol of Fe, is the heaviest element that can be fused due to the Coulomb barrier after iron fusion becomes too high and requires too much energy for fusion to occur, instead fission occurs which is the opposite process in which heavier elements are split into lighter elements.

At each stage of heavier elements being fused and created temperatures and pressures in the core increase allowing the next stage of fusion to occur due to an increase in energy. Until Iron is fused which is the critical fusion reaction in which it is the first reaction to use more energy than it generates. This causes a net loss of energy and the gravitational force slowly starts to overcome the pressure force. At this point the core reaches temperature of around 1010 K and mass continuously enters the core increasing density. Several processes take place in the extreme conditions of the star’s core which eventually leads to the supersonic collapse of the star to reverse and expand outward out supersonic speeds, what results is a catastrophic explosion known as a supernova. This explosion sends debris at tremendous speeds through the local galaxy including heavy elements, gases, and dust [30]. This could affect the evolution of the local galaxy and star and planet formation in unknown ways over millions of years.

A supernova is the first late evolutionary stage that occurs for BSGs and is an explosion of the star as extreme amounts of forces interact with the core and material in the star’s interior. The next stage depends on the amount of mass held within the star’s core. If there is less than 3 Mʘ within the core after the supernova, then it will form a neutron star which are stars with extremely high densities due to the star containing a few solar masses in a region of around 10 km [31]. If there is more than 3 Mʘ within the core after the supernova, then the core will collapse into a singularity with extremely high gravitational forces known as a black hole. Due to the mass of the BSG, it will become a stellar mass black hole [32] as opposed to a supermassive black hole which are theorised to be millions of times more massive than the sun and are also theorised to be found at the centre of large galaxies.

# 2. AIMS AND OBJECTIVES

The main aim of this project is to research and understand the fundamental formation of blue supergiant stars and how these stars evolve into, through and past their main sequence phase into more impactful celestial phenomena such as supernovas and black holes. The objectives to achieve this aim are:

1. To study and analyse the conditions that lead to the formation of a blue supergiant star by researching the pre nebula of existing blue supergiant stars
2. To investigate the potential evolutionary path and how the death of a blue supergiant star can affect the surrounding universe either by a supernova, black hole, or other factors
3. To compare the stellar composition, structure, magnetism (and features such as stellar flares and stellar spots) and processes such as nuclear fusion of blue supergiant stars to solar-like stars

# 3. METHODOLOGY, RESULTS AND DISCUSSION

## **3.1 BSG Formation & Competing Theories**

As mentioned before in section 1.2, stars are thought to form in gas clouds known as nebulae. These are cold, dense regions of space that contain gas, dust, and vast amounts of hydrogen particles. The initial conditions in the nebula will generally determine the type of star born within. For high mass stars compact clumps of hydrogen densities around 1023 – 1024 cm-2 are found to be present. These hydrogen densities are much larger than those found in the conditions of stellar mass star forming nebulae [33]. It is found that smaller mass clumps of hydrogen densities lower than 1023 cm-2 do not lead to massive star formation, therefore it can be shown that massive star formation requires specific initial conditions of very high proportions. These conditions can be observed through several types of cloud surveys being near HII regions: CS-molecule surveys are conducted for dense molecular gas, similar to high mass star forming nebulae [33]. These surveys of gas and dust have been carried out and have discovered massive star forming nebulae have gas temperatures between 10-50K and gas masses ranging from 100s – 1000s of solar masses. [33]

As mentioned in section 1.2, there is a generalised four step process of the basic theory of massive star formation: The Compression phase, the Collapse phase, the Accretion phase, and the Disruption phase. The process stars at a pre-existing molecular cloud with initial conditions as mentioned above.

The Compression phase begins with the formation of a cold molecular starless core of around 100 Mʘ or a starless clump of around 1000 Mʘ. These cores are theorised to form multiple, gravitationally bound, massive protostars. This means that supersonic turbulence from a source, either a combination of internal forces or an external source possibly from a distant supernovae shockwave, produces localised pockets of gas which can remain gravitationally bound and when combined with turbulent and pressurized clouds allows sufficient material to be available in the cores of giant molecular clouds during high mass star formation. However mechanical energy must still be infused into the clump to maintain a quasi-equilibrium state between the turbulence and gravitational forces. This can be done either through the kinetic energy of outflows and accretion shocks from within the core, or energy from outside the core flows down into smaller size scales into the core. It is theorised that magnetic fields play a role in this stage of the molecular cloud. There are differing theories that the compression phase is a transient state caused by the random motions in the cloud [34]. This implies that some cores collapse, marking the beginning of the collapse phase, whilst in other parts of the cloud compression continues. The two different theories are named as competitive accretion and monolithic collapse with the former being connected with the transient phase theory and the latter being connected with the core theory with energy being injected into the core.

The Monolithic collapse theory [35] states that the mass of the final star is associated with the initial mass necessary for massive star formation. Also, turbulence plays an important role in this theory as is stated “If there are bulk motions of the embryo star, its protostellar core participates in those motions” (Zinnecker & Yorke, 2007). It is also stated that the competition for infalling material is between close members of a multiple system containing multiple cores. On the other hand, the competitive accretion theory [36] states that material can come from various sources in the nebula to make up a particular star and also that multiple protostars are often formed at one time therefore leading to a competition for molecular material.

A study has been carried out [37] that has studied the effects of magnetic fields on high mass star formation by studying the evolution of clumps and cores formed as the densities of turbulence fluctuated and considering both magnetic and non-magnetic cases. The study found that the cores in magnetic cases are unlikely to reach a hydrostatic state due to magnetic forces combining with radiative forces and preventing a gravitational collapse of the star. If a hydrostatic state is not able to be reached, then monolithic collapse cannot occur. As a conclusion it was found not all cores observed in the molecular clouds will form stars, and magnetic fields could reduce core formation efficiency by delaying the collapse of individual cores.

The next stage is the collapse phase in which gravity must dominate over magnetic, turbulence, pressure, and rotation forces in order to cause the protostar to collapse and eventually form a star. In order for gravity to become dominant, the Jeans mass must be defined as the smallest mass for gravity to become dominant and is given by the formula [33]:

(4)

Where

MJeans is the Jeans mass

Tgas is the gas temperature [K]

is the density [g cm-3]

Turbulence acts as a repulsive force therefore acts against gravity, if turbulence is supersonic, exceeding the speed of sound, then it exceeds gas pressures. Once the gravitational force dominates over other forces in an optically thin gas that is capable of radiating compressional heat, it will remain dominant, and the gas will collapse on a time scale known as the free fall time scale. This timescale is given by [33]:

(5)

This formula shows that the densest parts of the cloud collapse the faster than less dense parts of the cloud, therefore the collapse is non-homogeneous meaning that the densest parts eventually become optically thick. Being optically thick allows increases in adiabatic heat transfer increases which causes a dramatic increase in pressure. As gravitational forces increase, gravitational collapse occurs and as a result, centrifugal forces increase as a consequence of the conservation of angular momentum. It is at this point that accretion disks and a flattening of structures becomes a projected result of gravitational collapse.

The accretion phase follows the after the non-homogeneous collapse of the clump of gas and dust into a protostar. The accretion phase involves mass entering the protostar via material travelling from outside sources, onto and along the accretion disk and finally into the core. As stated before, the core becomes optically thick, and collapse stops in the central regions at this point. It is a common phenomenon for supergiant stars to become binary stars therefore during this phase and after collapsing it is possible for multiple cores/protostars to form. In the case of competitive accretion, it would be at this stage where protostars would compete for material in order to gain mass and increase in size. More often than not, a single protostar ends up absorbing the majority of the mass into it, resulting in this star becoming the primary star in the system once the star cluster has formed.

The core will become quasi-hydrostatic meaning that pressure forces balance gravitational forces on a dynamical timescale [33]. The core will also maintain an increasing amount of mass if there is a continuous flow of material onto the core. This material will be transported to the core from the accretion disk, which is a compact, spinning disk of dust and gas that generates large amounts of friction and therefore heat, and light is produced. A similar phenomena is seen to occur with black holes.

The differences between stellar mass and massive star formation include the role of radiative pressure, the difference in the increase of mass through accretion, and differences in luminosity values. Luminosity is a critical component during accretion of high mass star formation, due to the luminosity of the accreting objects changing as material is transported through the disk. A primary difference is that high mass stars reach the main sequence very quickly and still accrete mass and continue growing as they evolve up the main sequence phase. Whereas stellar mass stars spend on average 30 million years getting to the main sequence phase and once it does, its mass remains effectively constant throughout the main sequence phase. It is also believed that high mass star formation has much higher accretion rates to accommodate for the large masses and much shorter periods of time getting to and spent on the main sequence lifetime.

Hydrogen burning commences in BSGs very quickly when compared to stellar mass stars, it will commence in high mass stars depending on their accretion rate. For example, a high mass star forming via accretional growth at a rate of 10-4 Mʘ yr-1 will begin core hydrogen burning when a total mass of 9Mʘ has been accumulated in the star [33]. If a star were to have a higher accretional growth rate than 10-4 Mʘ yr-1, then the star would accumulate more than 9Mʘ by the time hydrogen burning commences. It is shown that higher accretional growth rates result in hydrogen burning commencing in stars when larger masses have accumulated than lower accretional growth rates. This implies that there is a set amount of time that high mass stars spend pre main sequence gathering mass, therefore those at higher accretional growth rates will accumulate more mass in the set timeframe than those at lower accretional growth rates. It is believed that high mass stars generally reach the main sequence in less than 150,000 years [38]

Radiative forces play little to no role in the formation of stellar mass stars but play a vital role in high mass star formation and lead to unique and characteristic effects. Radiative pressure forces cause an outflow of material out of the star known as stellar winds. In order to gain mass, the inflow of material must be greater than the outflow. Once an accreting high mass star has evolved onto the main sequence phase, it does not become observable because the star’s accretion disk obscures the star from an observers view. In order to become visible, the disruption phase must take place in which the accretion disk is destroyed, and the star becomes visible.

At the beginning of the disruption phase the star has been producing radiation in the form of hydrogen ionizing photons due to its high luminosity values. This leads to the ionization of immediate material around the accreting star. Material that is closer to the star becomes bound due the escape velocity being much higher than it is when further away from the star. Material that is further away, and subjected to a lower escape velocity, expands outwards from the star causing a portion of material to escape from the star. Next the accretion disk becomes ionized and as a consequence produces a disk wind, similar to the stellar wind, in which there is an outflow of material from the disk. This disk wind can interrelate with the existing stellar wind from the star and cause, with the combination of outward expanding radiative forces, the photoevaporation of the disk via the ionizing radiation [39]. After this process, the star becomes visible, the disruption phase ends, and the accreting star cluster or system is located on the main sequence phase and is still gaining mass.

## **3.2 Nuclear Fusion**

As aforementioned in section 1.3.1, BSGs undergo nuclear fusion via the CNO cycle which is the reaction of hydrogen with carbon, nitrogen, and oxygen to create helium and energy. The reaction is catalytic meaning that there is no net loss of the carbon, nitrogen and oxygen involved in the reaction. This means that even though each nuclei is consumed in a step of the process, they are later recreated in the process.

The cycle starts with Carbon-12 reacting with a proton to create Nitrogen-13 and some electron neutrinos. Nitrogen-13 is an unstable isotope of Nitrogen and so it undergoes beta plus decay to emit a positron and Carbon-13. Carbon-13 then reacts with another proton to create Nitrogen-14, which is stable, and some gamma ray photons. Nitrogen-14 then reacts with another proton to create Oxygen-15 and gamma ray photons. This reaction is the slowest out of all the reactions, lasting up to a few million years in the cycle and is therefore an important step for the control of energy production in BSGs. Like Nitrogen-13, Oxygen-15 is unstable and also undergoes beta plus decay releasing a positron and creating Nitrogen-15 and some electron neutrinos. The final step is Nitrogen-15 reacting with a fourth and final proton to create Helium, known as an alpha particle and Carbon-12 to restart the cycle. The Carbon-12 will restart the cycle by reacting with a proton and the net reaction is an input of 4 hydrogen particles and an output of an alpha particle and energy [40].

A consequence reaction to take note of from the CNO cycle is the positrons released in the beta plus decay of Nitrogen-13 and Oxygen-15 are the anti-particles of electrons, they share the same properties apart from they have the opposite electrical charge. When particles come into contact with their respective anti-particles, they will almost instantly annihilate each other and release gamma photons and around 2 MeV of energy. The neutrinos created in the cycle will carry energy away when they escape from the star.

There are variations of the CNO cycle much like the proton-proton chain of stellar mass stars. They involve different reactions leading to the creation of different isotopes and different energy releases. The CNO-II cycle occurs in place of the last step of the CNO cycle, instead of Nitrogen-15 reacting with a proton to create Carbon-12 and an alpha particle it reacts with a proton to create Oxygen-16, gamma ray photons and an energy release of 12.13 MeV. The cycle then continues as follows:

168O + 11H  179F + 0.60 MeV

179F 178­O + e+ + 2.76 MeV

178­O + 11H 147N + 42He 1.19 MeV

147N + 11H 158O + 7.35 MeV (6)

158O 157N + e+ + 2.75 MeV

Total 26.78 MeV

Other reactions occur due to varying processes in steps of the cycle. Other bi-products include Fluorine-17, Oxygen-17, and Oxygen-18 to name a few. Each CNO cycle has a probability of occurring with the primary cycle being the CNO-I cycle, and the CNO-III and the CNO-IV only being significant reaction cycles in the most massive O and B type stars. These cycles have a low probability of happening in small O and B type stars. Overall, each process releases energy and if comparable to the Sun there will be extremely high amount of reactions per second, which increases with luminosity. The Sun has approximately 9.3 x 1037 [41] reactions per second each releasing around 26 MeV, so if the number of reactions per second is increased with an increasing luminosity, and BSGs have much larger luminosity values than the Sun, then it is clear to see that BSGs produce extraordinarily high amounts of energy. For example taking values of Rigel from table 2 and assuming an energy production of 26.78 MeV, ~ 4.61x10-12J, and taking the luminosity value of 120,000 Lʘ, ~4.596x1031 W. These values lead to:

Comparing to the Sun which has approximately 9.3x1037 reactions per second, it is clear to see that a BSG has many more reactions per second and therefore it can be seen why BSGs have much shorter lifetimes.

An important parameter to mention is radiative pressure which is the outward force produced in the interiors of massive stars and opposes the gravitational force. Both forces end up in a hydrostatic equilibrium meaning that both forces are equivalent and neither force dominates. Radiation pressure is given by the formula [42]:

(7)

Where

a is the radiation constant

T is temperature [K]

Prad is the radiation pressure [J m-3 or Pa]

The radiation constant stays constant therefore the determining factor for radiation pressure is temperature meaning that hotter stars produce higher values of radiative pressure to obtain an equilibrium state against gravitational forces. It can therefore be shown that as temperature increases in the interior of stars, so too does the radiative pressure increase.

Due to BSGs having higher gravitational forces and temperatures, they undergo fusion at much faster rates than solar mass stars, and there exists a corelation between mass and main sequence lifetime. During the hydrogen fusion phase of the CNO cycle is when the star is located on the main sequence of the Hertzsprung-Russell diagram, where the majority of stars are located. There exists a timescale that governs the time that a star will remain on the main sequence phase and this is known as the nuclear time scale and is given by the formula [43]:

(8)

Where

is the nuclear time scale [yr]

M is the mass of the star [Mʘ]

Mʘ is the solar mass or mass of the Sun [kg]

L is the luminosity of the star [Lʘ]

Lʘ is the solar luminosity or the luminosity of the Sun [W]

For example, taking Aludra from table 2 and inputting the given values into equation 8 leads to a nuclear time scale of:

This value will depend on the mass of the star as well as the luminosity of the star, but this equation shows an approximate value of the order of a few million years.

There also exists a relationship in which more massive stars have shorter main sequence lifetimes [44]. This is due to more massive stars generally having higher luminosities and stronger gravitational forces and therefore burn fuel at a faster rate. The CNO cycle takes place in these stars when they are located on the main sequence phase of their lifetime which corresponds to hydrogen burning and once the majority of hydrogen fuel is used up then another source of energy must be found. The fusion process to take place after the CNO cycle is the fusion of Helium into Carbon known as the triple alpha process. This reaction starts with two alpha particles fusing to create Beryllium-8 and gamma ray photons, The Beryllium then fuses with another alpha particle to create Carbon-12 and gamma ray photons [40]. This process replaces the CNO cycle in the core, meanwhile hydrogen burning moves to an outer shell of the star to create a source of Helium. It is at this point where the star begins its journey off the main sequence and towards its post main sequence evolution.

Eventually Helium starts to run out for fusion, therefore another fusion process is required. Gravitational forces slightly dominate again over radiative forces and cause the core of the star to collapse slightly increasing core temperature to around 3x108 K. At these temperatures Carbon-12 fuses with remaining Helium in the core to produce Oxygen-16 causing the star to now have three sources of energy. Carbon-12 fusion into Oxygen-16 in the core, the triple alpha process in an outer shell around the core and Hydrogen fusing into helium in the outermost shell. Once all helium in the core has run out, the core now being composed mainly of Carbon-12 and Oxygen-16 contracts again, radiative pressure increases due to another temperature increase to around 5x108 K. Now Carbon burning commences in the form of three possible reactions:

126C + 126C 24 12Mg + This is the least likely reaction

126C + 126C 2311Na + 11H (9)

126C + 126C 2010Ne + 42He

Fusion into Neon or Sodium are both equally as likely. Once Carbon becomes depleted in the core, it once again contracts and increases in radiative pressure and temperature to around 109 K and a very important process occurs after carbon burning which is known as photodisintegration. At a temperature of around one billion Kelvin, the star is now hot enough for its spectrum to extend into the gamma ray section, meaning that fusion reactions that release energy in the form of gamma ray photons can be reversed. Some of the Neon produced from Carbon burning will undergo photodisintegration [29]:

2010Ne + 168O + 42He (10)

The alpha particles that form as a biproduct of Neon photodisintegration will react with the Neon that did not under photodisintegration. At temperatures of around 1.5x109 K this process known as Neon burning occurs:

2010Ne + 42He 2412Mg + (11)

This will change the composition of the core to be composed mainly of Oxygen and Magnesium. This process continues until Neon becomes a scarce fuel, the core contracts again and temperature increases to around 2x109 K, around these temperatures Oxygen burning occurs to fuse together to create Silicon:

168O + 168O 2814Si + 42He (12)

It must be noted that alpha particles created in the reactions of Neon burning and Oxygen burning quickly disappear due to their involvement in fusion reactions with heavier elements. Whilst Oxygen burning occurs, other process take place in the outer shells of the star’s interior. The lightest element, hydrogen, continues fusing in the outermost shell, Helium in the next shell closer to the core, then Carbon, then Neon and Oxygen burning in the core.

Once Oxygen fuel runs out then once again the core contracts, increases in radiative pressure and increases to a temperature of around 3x109 K at which the photodisintegration of Silicon can occur:

2814Si + 2412Mg + 42He (13)

This reaction produces a source of alpha particles which will rapidly react with Silicon that did not undergo photodisintegration by the following reactions:

2814Si + 42He 🡪3216S + γ

3216S + 42He 3618Ar + (14)

3618Ar + 42He 4020Ca +

This process of alpha particles reacting to create heavier elements continues until a critical point is reached, the fusion of Iron. Iron has an atomic mass of 56 meaning that the Coulomb barrier potential becomes too high for iron and any element above it to be fused. After iron, fission can occur which is the opposite process of fusion in which heavy elements split apart into lighter elements. Iron being created also holds another limit of nuclear fusion. It is the first reaction in the whole process that uses more energy than it generates, this means that for every iron nuclei created via fusion there is a net loss of energy in the star. Figure 3 shows a diagram of each fusion shell located in a high mass star. Each subsequent fusion process lasts shorter and shorter as the element increase in atomic mass. With Helium burning, one of the early and light element fusion processes, lasting several 100,000s years. Oxygen burning, a middle ground element, lasts only several months and Silicon

Burning, one of the final fusion processes before the star begins to die, lasts only 1 day [29].

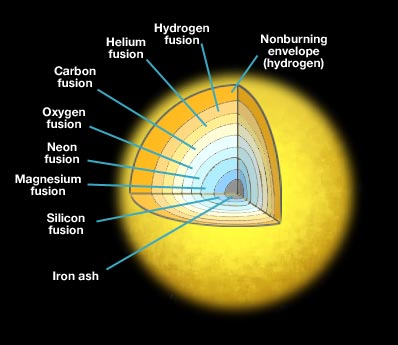


Figure 3: An illustration of all fusion stages occurring in the final moments in a high mass star's lifetime. The core is composed of the heaviest available element, iron, and each subsequent shell represents a lighter element fusion all the way to hydrogen fusion in the outermost shell [45]

## **3.3 Stellar Winds & Mass Loss**

As mentioned in sections 1.3 and 3.1, BSGs experience characteristic stellar winds in which there is an outflow of material from the star. This material can take the form of gas, dust, and particles. Once hydrogen burning commences in the CNO cycle in high mass stars, large amounts of radiative pressure is generated which causes an outflow of material out of the star. This clearly leads to mass being lost form the star and over long periods of time, this can add up to vast amounts of mass. All stars are thought to lose mass over their lifetimes through various procedures. The Sun can lose mass through solar winds (although the mass loss experienced by the Sun is a lot less than what BSGs experience), solar flares, or coronal mass ejections (CMEs). The last two processes are determined by the magnetic properties and processes of the star. Through a combination of these processes, the Sun loses around 3x10-14Mʘ yr-1 [46]. For comparison, and to recall, table 3 shows the measured mass loss of some example O type and B type stars. The average magnitude of mass loss measured in Mʘ yr-1 is 10-6 which is a lot higher than the mass loss of the Sun. These values were measured by observation of various factors such as the stellar wind and in particular the P Cygni profile

As nuclear fusion occurs in the core of BSGs various reactions lead to the creation of gamma ray and UV photons. These photons are of high energy and therefore generate large amounts of radiation pressure. In some parts this pressure is high enough to overcome gravitational forces and cause the outflow known as the stellar wind. It could also be shown from equation (7) that radiation pressure increases with increasing temperature so as the core temperature increases, more radiation pressure could be generated via fusion and cause stronger stellar winds and higher mass loss rates. On the other hand, as the star undergoes later fusion reaction gravitational forces also become stronger due to the core contracting meaning that gravity still dominates despite the increase of radiation pressure.

As mentioned before, stellar winds are observed via their characteristic spectral profile known as the P Cygni profile which can undergo two characteristics, blue-shifted absorption dip and red-wing emission. Both of these characteristics are explained in section 1.3. Figure 4 shows an example of a P Cygni profile undergoing emission peaks and absorption dips.

Diagram

Description automatically generated

Figure 4:a) A P Cygni profile example showing an absorption dip and a broad emission line peak b) A star with an expanding mass shell demonstrating each process of the emission through the lettered steps. For example, at step C the shell is at its furthest from the star, so emission is at its strongest corresponding to the graph on the left [18].

The first step corresponding to step A is when blue-shifted absorption dip would occur. This involves the stellar wind absorbing some of the radiation emitted from the star as it moves towards an observer on Earth, the area of absorption corresponds to the shaded region on figure 4b. As the shell expands and gets further away from the star, absorption turns to emission and either the stellar wind scatters photons towards the Earth or when the stellar wind emits photons towards the Earth. Emissions is at its most intense when the shell is at its furthest distance away from the star corresponding to step C. Finally, as the shell recedes back towards the star, emission becomes less intense, and a continuum is reached until absorption occurs back at step A. Observations of this spectra can lead to values being determined through observations such as the stellar wind velocity, a parameter of the equation below [18].

Some papers (Lamers and Cassinelli, 1997) [47] (van loon et al. 2005) [48] suggest formulae for calculatable mass loss rates. The first formula is given by [47]:

(15)

Where

is the mass loss rate [Mʘ yr-1]

is the stellar wind velocity [km s-1]

R\* = Radius of the star [Rʘ]

L\* = Luminosity of the star [Lʘ]

Rearranging this equation to obtain mass loss yields equation 16:

(16)

Inputting the values of Rigel, for example, from table 2 with a stellar wind velocity of around 230 km s-1 and solar luminosity of around 120,000 Lʘ leads to a calculated mass loss rate of around 1.9x10-6 Mʘ yr-1. This result is relatively close to measured value given in table 3. The remaining mass loss values for the other stars are also given in table 3

The second formula is given by [48]:

(17)

Where

is the mass loss (another notation for ) [Mʘ yr-1]

Teff if the effective temperature of the star [K]

Rearranging for mass loss yields:

(18)

Inputting values of luminosity and effective temperature will yield the mass loss calculated from this equation. Table 3 (shown below) shows a list of BSGs in which the appropriate values could be found, the measured mass loss from observations and the calculated mass loss from the above equation. The solar luminosity value used was that of the Sun’s luminosity and is given by 3.86x1026 W. As shown, this equation leads to values that are just as close to the observed values when compared to equation 16. They are not exact values but are only off in some cases by an order of magnitude of 4.

Table 3 shows some potential correlations between the different factors of BSGs and mass loss rates. Firstly there is a correlation between a star’s luminosity and the calculated mass loss from equation 18, with higher luminosities having higher mass loss rates. Also there is a general correlation between calculated mass loss and temperature, with higher temperatures generally having higher mass loss rates. The second correlation makes sense in the fact that higher temperatures result in higher levels of radiation pressure and radiation pressure leads to stellar winds. Therefore an increasing temperature would lead stronger stellar winds and from a combination of tables 2 and 3 it can be seen that higher stellar wind speeds correlate to higher mass loss rates.

Table 3: Measured and calculated mass loss values of sample collection of BSGs

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Star Name** | **Effective temperature (K)** | **Star Luminosity (Solar luminosity)** | **Star temperature (K)** | **Measured mass loss (Mʘ/yr) (estimated)** | **Mass loss from equation 18 (Mʘ/yr)** | **Measured mass loss from equation 16 (Mʘ/yr)** |
| Naos - Zeta Puppis | 42000 | 813,000 | 40,000 | 3.50E-06 | 1.22821E-08 | 7.07E-06 |
| Alnilam | 19382 | 537,000 | 27,500 | 6.00E-07 | 3.74373E-09 | 3.69E-06 |
| Omicron2 Canis Majoris | 12523 | 220,000 | 15,500 | 1.36E-06 | 9.90976E-10 | 6.32E-07 |
| Rigel A | 11122 | 120,000 | 12,100 | 9.00E-07 | 4.80061E-10 | 1.91E-06 |
| Aludra | 12939 | 105,442 | 15,000 | 2.00E-09 | 4.90734E-10 | 8.46E-07 |
| Saiph | 17659 | 56,881 | 26,500 | 1.00E-06 | 3.61298E-10 | 5.05E-07 |

A potential difference between equations (15) and (17) is the differing values within the equations, for example equation (17) considers effective temperature which is a governing factor of radiative pressure which is one of the main cause of mass loss in BSGs. Equation (15) does not contain a temperature term therefore this equation could be missing a term to calculate radiative pressure. Also, equation (15) contains a radius term which could be used to calculate gravitational forces but is missing a term for mass in order to calculate a gravity term according to Newton’s law of universal gravitation given by the formula:

(19)

Where

g is the surface gravity of an object [m s-2]

G is the gravitational constant = 6.674x10-11 m3 kg -1 s-2

M is the mass of the object [kg]

r is the radius of the object [m]

## **3.4 Binary Systems**

A binary system, as stated in section 1.3 is a system of 2 or more stars that orbit and interact with each other. The system is often composed of a primary star of higher mass , such as a BSG, and a secondary or companion star of smaller mass. This secondary star could be a white dwarf star, a neutron star, a small main sequence star, or some other smaller mass star. For example, Rigel which is a BSG given in the tables above in a binary system, with Rigel A being a BSG and Rigel B being a white dwarf star. During the collapse phase of the formation of high mass stars, it is possible for multiple clumps of gas to form multiple cores and protostars going into the accretion phase. The competitive accretion theory [36] then suggests that these protostars compete to gain mass with one protostar accreting a majority of the available mass and ending up as the higher mass star.

Many O and B type stars have been found to be in a binary systems, a 2012 study of OB galactic clusters (Sana et al. 2012) [49] reported an interacting binary fraction of 0.69 0.09 for O type stars in the cluster. This shows that nearly 70% of those O type stars observed were part of binary systems and this can cause an extreme effect on the stars’ evolution. Stars being in a binary systems can have further effects on mass loss if the binary system encompasses the Roche-lobe. The Roche-lobe as stated in section 1.3 is a region around a binary system in which material that remains within the boundary of the Roche-lobe will continue to be gravitationally bound to the star. As stars evolve, they can expand and so material from either star can pass this boundary allowing it to transfer to the other star or transfer to the surrounding interstellar medium if the gravitational forces involved in the system are sufficiently strong. Recall figure 2 showing an illustration of a Roche-lobe in a binary system.

Because of BSGs having very short lives when compared to other stars, it will be seen that for binary systems in which the primary star is a BSG and the companion star is for example a neutron star, which have far longer lifespans, the companion star will outlive the BSG. This could lead to a new system in which the old companion star becomes the new primary star [50]. It could also be possible during mass transfer episodes that large amounts of mass are transferred between stars to an extent in which the primary and companion star switch if the primary star loses too much mass.

The evolution of the companion star in the binary system will also be heavily affected due to mass transfer. Once material passes the Roche-lobe boundary, known as Roche-lobe overflow (RLOF), and mass is transferred to the companion star, its luminosity and temperature will increase and processes occurring in the star will be affected. For example, radiation pressure will increase due to an increase in temperature which in turn could affect the forces of the star over time. It is also reported that during a mass transfer episode, mass loss via stellar wind increases due to the increased outflow of material [50].

There are other methods for stars to cross the Roche-lobe boundary. The method discussed so far involves stars expanding as they evolve, and their shells can cross the boundary for mass transfer to occur. This means that as the star evolves its radius increases and to conserve angular momentum, the orbit of the companion star must decrease. This reduced orbit decreases the size of the Roche-lobe and pulls the companion star closer to the Roche-lobe boundary and makes a RLOF or a mass transfer episode more likely to occur.

Some of the stars in table 3 are part of binary systems, such as Rigel B, Alnitak A and another BSG known as Mintaka (part of the Orion’s belt constellation). These stars being part of binary systems could alter their mass loss and account for the differences in observed and measured values, for example equation 18 might not consider some stars being in binary systems, resulting in values that are completely off from the actual value.

## **3.5 Magnetic Processes**

A lot of stars are known to have magnetic fields, the Sun has a magnetic field that is altered by various phenomena both on and below the surface. A study of magnetic fields in high mass stars (wade et al. 2013) [28] named “magnetism in massive stars” (MiMeS) takes a range of 550 OB stars from a luminosity range from V to Ia and aims to analyse magnetic field data. A handful of these stars were already known to have magnetic fields and are used as a reference point for the MiMeS project. This leaves a sample size of around 525 OB stars, of which approximately 430 are B type stars and approximately 90 are O type stars. Of the 430, 32 stars were found to be magnetic, and of the 90, 6 were found to be magnetic. Of all the stars found to be magnetic, all contain important dipole components and strengths ranged from 100’s Gauss to 10,000’s Gauss. Comparing to the Sun’s magnetic fields which at their strongest in sunspot regions, can reach up to around 3000 Gauss. Overall, this project concluded that with current instrumentation, around 7% of massive stars are detectable to host a magnetic field. [28].

This project shows that it is possible for high mass stars to have magnetic fields and those that do are dipolar in character. This means that there is a north pole and a south pole that create a closed loop field around the star and these fields can have very strong field values when compared to smaller stars. There is a general correlation magnetic fields of high mass stars are structurally simpler than that of smaller stars such as the Sun. The magnetic fields of hotter, more massive stars are also generally much stronger than those found in cooler stars [28]. It was also found that magnetic characteristics of the magnetic fields of O and B type stars are very similar implying very similar processes and properties between the two types of stars in terms of magnetic processes.

Another study of magnetic fields in OB stars [51] named “The B fields in OB stars” (BOB) survey, is a very similar experiment to the MiMeS survey in which multiple O and B type stars were observed and a similar experiment was conducted to analyse magnetic field activity in old O type and young B type stars. This study found a similar result in which the majority of detectable fields are dipolar, have a vast range of field strengths from hundreds of Gauss to up 20,000 Gauss, and at the current time only a small fraction of fields could be detected on OB stars. This comes down to a limitation of current technology, as stated by (wade et al. 2013) “The MiMeS survey therefore establishes that the basic physical characteristics of magnetism in stellar radiative zones remains unchanged across more than 1.5 decades” [28].

Several processes can influence or be caused by magnetic properties in stars, one of the most common being stellar spots which as mentioned in section 1.3 in the context of the Sun, where they are known instead as Sunspots, are areas on the surface of a star in which the localized magnetic fields are much stronger than the rest of the star. They appear as dark spots on the surface of the star because the stronger magnetic fields prevent some heat from reaching the surface of the star and so it is a cooler region on the surface. If the magnetic field lines of the star get too close to these active regions, then they can get tangled and cause a large release of magnetic energy in the form of radiation, this is known as a stellar flare [10]. Processes in the stars’ interior also influence the evolution of magnetic processes, with the Sun’s interior having both a radiative zone and convective zone in which the forms of energy transfer dominate in their respective zones. A BSG will have a different interior than the Sun, O type stars have a convective core, and the majority of the star’s interior is radiative, meaning that in the core convective transport dominates and in the outer shell, radiative transport dominates.

Convective transport occurs when regions of plasma in a star’s interior become hotter and decrease in dense, due to a difference in density, the hotter plasma rises as the colder, more dense plasma sinks down and pushes the hot plasma up. This process continues until the hot plasma reaches the edge of the core where radiative energy transport dominates in the vast majority of the interior of the star. Energy from the hot plasma in the core is taken away and the plasma becomes colder and increases in density. It will then sink back down into the core and push new hot material towards the boundary of the core. From the core, radiative energy transport dominates which is when energy is transferred in the form of electromagnetic (EM) radiation through and out of the star’s interior. These processes in the star’s interior cause turbulence that could interact with the magnetic field lines and cause magnetic phenomena such as stellar spots and stellar flares.

Another common magnetic process that frequently occurs in the Sun are flares, the release of magnetic energy if the magnetic field lines become entangled from active regions of extreme magnetic fields strengths. B type stars have are observed to have a very thin convective layer, shown in figure 5 referred to as a convective envelope, below the surface of the star [26] (note that figure 5 has been edited to show more clearly the convective envelope of a B type star) sometimes. It could be possible for processes known as dynamo action to occur and lead to a magnetic field rising via magnetic buoyancy and emerging on the surface of the star. It is currently theorised that there is on convective envelope in O type stars. Figure 6 shows an illustration of an emerging magnetic field originating from the convective envelope in a massive star. Therefore, through dynamo action and magnetic buoyancy it could be possible for massive stars such as BSGs to experience stellar spots.

If stellar spots can occur on massive stars, then it can be shown that it theoretically should also be possible for stellar flares to occur for massive stars. As stated before, stellar flares occur when the magnetic field lines interact with the strong magnetic field of stellar spots and become entangle or distorted, in the context of the Sun the average magnetic field strength of a Sunspot is around 3000 Gauss [26]. If the magnetic fields of hot, massive stars are generally found to be much stronger than those found for smaller mass stars [26], then it is hypothesized that stellar spots on the surface of massive stars will also have much stronger magnetic field strengths than Sunspots on a stellar mass star. A study on magnetic spots on hot massive stars (Cantiello and Braithwaite, 2011) [52] showed that it is possible for emerging magnetic fields to reach the surface and create stellar spots. However, they found that the magnetic fields of these surface-active regions are localized and were found to be only a few hundred gauss.

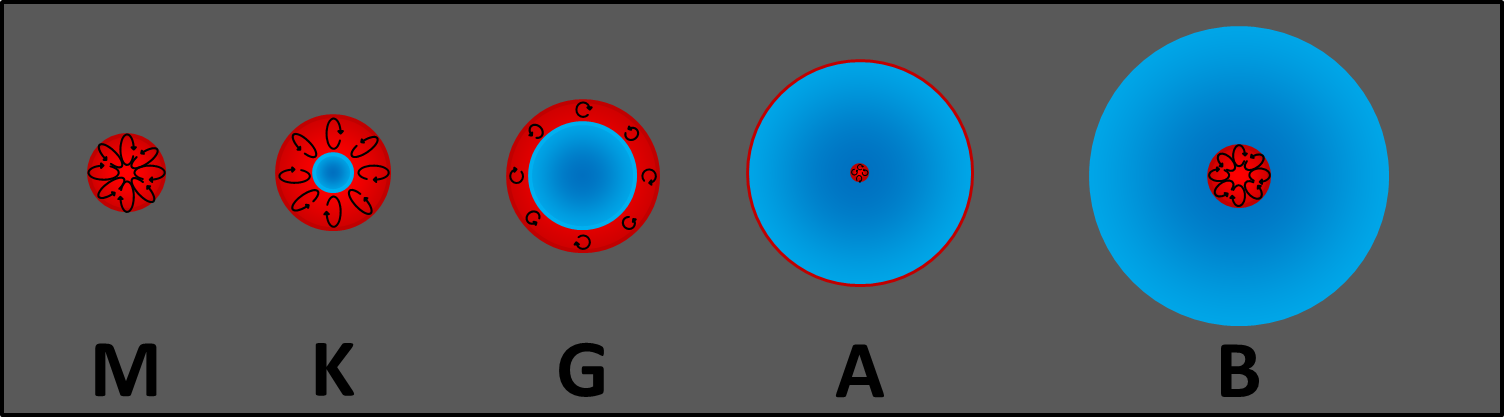


Figure 5: An illustration of convective and radiative regions of M type to B type stars. Red zones represent convective transport regions and blue zones represent radiative transport regions [53].

Diagram

Description automatically generated

Figure 6: An illustration showing an emerging magnetic field on the surface of a massive star. Processes in the convective envelope could potentially allow a magnetic field (dotted line) to pass through the radiative layer and emerge at the surface and the photosphere of the star, potentially leading to the creation of a stellar spot [52]

Another important property of massive stars that could provide evidence for strong magnetic fields in massive stars is that massive stars on the main sequence usually rotate rapidly with typical velocities of around 150 km s-1 which could increase the strength of magnetic fields [52]. This is caused by dynamo excitation and turbulent convection which allows for magnetic field strengths of up to 2 KiloGauss. Therefore, dynamo actions in massive stars could depend on rotational velocities.

There exists a theory of the origins of magnetic fields of O, B, and A type stars known as the fossil origin hypothesis [54]. This theory is currently the most popular and widely accepted theory of the origins of massive star magnetic fields. The theory suggests that the magnetic field detectable for some O and B type stars are the remnants of the magnetic field that would have been present in the magnetic cloud during the stars formation and lasts for the most of the star’s lifetime due to the field being very stable. This theory is heavily supported for A type stars and generally accepted for O and B type stars. It was also found that there was no correlation between the mean magnetic field strength of OB stars and the projected rotational velocity meaning that the only factor that is affected by the rotational velocity in massive stars is dynamo action and the resulting magnetic field strengths would depend on the type of processes that occur as a result of dynamo action. This result is consistent with the fossil origin theory.

A final study (Kholtygin et al. 2010) [54] also investigated magnetic fields in massive stars and found an important result. Figure7 shows for B type stars how the mean magnetic field strength evolves over the main sequence lifetime. A clear decrease in mean magnetic strength can be seen as the star evolves through the main sequence. It was found that over the main sequence lifetime of a B type star, its magnetic field strength decreases by a factor of 5-7. This results implies that during the main sequence, processes in the stellar interior cause changes to dynamo action and as a result cause a decrease in magnetic field strength which could in turn affect magnetic processes post main sequence. This result could imply why it was difficult for the MiMeS and BOB surveys to find a significant fraction of the sample stars with detectable magnetic fields.

Chart, line chart

Description automatically generated

Figure 7 The mean magnetic field strength, B, as a function of relative stellar main-sequence lifetime, [54].

## **3.6 Evolution and Death Stages**

As mentioned in section 3.2, as fusion fuel runs out for a particular process in BSGs, the core of the star contracts, increases in temperature, and therefore radiation pressure, which allows for another fusion process to take place utilising a heavier element. Multiple fusion processes occur in the cores of BSGs as fusion of lighter elements occurs in outer subshells, shown in figure 3. Nuclear fusion occurs until iron, which has an atomic mass of 56, is formed. Recall that the fusion of iron uses more energy than it produces, therefore each reaction of iron fusion causes a net loss of critical energy in the core. As a consequence of energy loss, the starts to collapse as gravitational forces slowly start to dominate over radiation pressure, causing the core to contract one final time, causing an increase in temperature and density. However, because there can be no more fusion reactions, there can be no more energy production to provide a balancing force for the now dominant gravitational force.

At this point the core reaches temperatures of around 1010 K, the temperature at which iron nuclei begin to photo disintegrate in a last resort attempt to halt the core collapse, this reaction produces alpha particles, Helium nuclei, protons, and neutrons. However, the energy produced in this reaction is absorbed in the surrounding core resulting in a faster core collapse than before which is capable of reaching supersonic speeds. As the core collapses further, pressure and density increase to extreme amounts, density is high enough for electrons to become degenerate and they start to produce a degeneracy pressure. This degeneracy pressure increase as the core continues to collapse until it reaches a high enough level of energy for electrons to react with protons to create neutrons and electron neutrinos [55].

But as this reaction takes place, the number density of electrons decreases resulting in the core collapse to speed up. At this point the core has reached a temperature of around 1012 K and a density of around 3x1017 Kg m-3 and at these values, neutron degeneracy can occur. Similar to electron degeneracy, this causes an increase in core pressure to such a degree that the collapse of parts of the inner core come to a halt and reverse outwards from the core in the form of a shockwave. The still infalling material outside of the core is moving inwards at speeds of up to 70,000 km s-1, or around 0.023% the speed of light. Once the infalling material comes into contact with the outward moving shockwave it slows down.

Back in the core neutrinos are being produced in vast amounts, these neutrinos hold substantial amounts of energy. Because of the number density of neutrinos in the core and the large density of material affecting the core, most of the neutrinos get absorbed along with their energy causing a huge spike of energy in the core. This causes the infalling material to reverse direction and blast outwards form the core resulting in a catastrophic collapse of the core known as a supernova [55]. The energy released in this collapse can be around 1044 J and during the explosion, the luminosity of the star drastically increases, by around a factor of 108. It is common for a supernova to briefly outshine the entire galaxy of which it is located due to the drastic increase in luminosity. The BSG known as Naos – Zeta Puppis from table 3 is an example of an evolved BSG that is nearing the end of its life. This star is likely to undergo critical collapse and become a supernova, and due to its mass, is likely to become a black hole.

There are two types of supernova, type 1 supernovae do not hydrogen lines in their spectra whereas type 2 supernovae do show hydrogen lines in their spectra. It is thought that type 2 supernovae are linked with stars that retain large quantities of hydrogen at the point of catastrophic collapse, and therefore type 2 supernovae are commonly associated with supergiant stars. On the other hand , type 1 supernovae are associated with stars that have either been completely stripped of their hydrogen mantle, this could potentially happen through binary interactions, or stars that have completely depleted their hydrogen fuel. Very late and very massive stars known as Wolf-Rayet stars are thought to completely use up their hydrogen fuel in the final stages of life and therefore produce type 1 supernovae with no hydrogen lines in their spectra [26].

The majority of energy released by the supernova is carried away by neutrinos into the interstellar medium, along with any elements created in the nuclear fusion processes that have occurred in the star’s short lifetime. It is this process through which heavy elements are created and spread throughout galaxies and the universe, and it is this reason the BSGs, and other O and B type stars are considered as the metal factories of the universe. Whilst the whole process of core collapse has been going on, mass has constantly been entering the core and this is the determining factor that will determine the next evolutionary path of the stellar remnant [30].

If there is less than around 3 solar masses in the core of the remnant, then the star will likely become a neutron star. Recall from section 1.4 that neutron stars have extremely high densities and gravitational forces due to having a mass of a few solar masses in a region that is around 10 km in radius [31]. The neutron star could then remain for tremendously long-time scales. However, if the core contains more than 3 solar masses then there is enough mass for an infinitely dense single point to form, known as a singularity. This singularity has the strongest gravitational force of any known celestial body, it is so strong that not even light can escape from it pull. This body is known as a black hole, and it is made up of several regions [32]. The singularity has already been discussed in section 1.4.

There lies a boundary of which, if crossed, there is no escape. This is known as the event horizon of the black hole and it is at this point that not even light can escape from the gravitational force of the black hole. If light were to enter the black hole in such a way that it does not get dragged in, but it cannot escape, then the light will orbit the black hole in a region known as the photon sphere. There is a similar region for which matter can orbit the black hole, known as an accretion disk, which is a similar concept to that discussed in section 3.1. If dust, gas, and particles orbit the black hole just outside the event horizon, then the energy of the motion of this matter is converted into heat energy. Due to the large amount of heat energy generated, the matter burns very bright and emits light which is observable and is how black holes are observed along with other phenomena such as quasars, which occur when powerful winds, similar to stellar winds out of a star, are driven out of the black hole which can also be observed and detected.

Both supernovae and black holes are processes that could have both constructive and highly destructive consequences. The effects of supernovae shall be discussed first.

Supernovae are extremely energetic explosions of massive stars, any celestial body, be it a planet, star, or space material, in the immediate vicinity at the time of catastrophic collapse will be subjected to extreme forces and temperatures. The shockwave caused by a supernova could even effect separate parts of the local galaxy or even area outside of the galaxy. For example, during star formation it is possible that a shockwave from a distant supernova could cause an external inward force to speed up the formation process of other stars located vast distances away from the original star. The other major consequence of supernova explosions is the spreading of heavy elements throughout the interstellar medium. These elements could find themselves being pushed into other star forming nebulae, planet forming systems or other processes that affect the evolution of the universe. In this way, supernovae could be considered as more constructive phenomena due to their destructive tendencies being limited to the immediate area around the explosion, whereas constructive consequences could potentially be observed vast distances away and in other galaxies to continue the evolution of the universe.

Black holes are widely seen as highly destructive phenomena due to their gravitational forces preventing anything that gets too close and passes the event horizon from escaping. However, this only effects material that passes the event horizon, any planets, stars, or material outside of the event horizon will not be pulled into the black hole. This implies that destructive effects of black holes are limited to material that comes into contact with the event horizon. A black hole can alter the orbits of celestial bodies such as stars and planets if they are close enough to feel a fraction of the gravitational pull but not too close that it will get pulled towards the black hole. However, if a star were to get too close to the black hole, if one side of the start were to cross the event horizon, then there would be an extreme gravitational gradient being experienced by the opposite sides of the star, the side in the black hole would experience forces much higher than the opposite side of the star and therefore the star would effectively be ripped apart.

The destructive forces are still limited to the immediate contact area of the event horizon. Similar to supernovae, the constructive effects can reach much further, since black holes play vital roles in the formation of galaxies and the evolution of the universe. Due to black holes having lifetimes much greater than the current age of the universe, they will exist for extraordinarily long times, therefore as the universe evolves, a single black hole will be present for a very long time and combined with the forces of other black holes of similar size and those of much higher mass, will eventually lead to the formation and evolution of galaxies and will alter the very evolution of the universe.

The majority of stars in table 1 will undergo critical collapse into supernovae, and the majority of these will evolve into black holes due to them having large amounts of mass. Some of the companion stars involved in binary systems of BSGs will alter the evolution of the primary BSG or will have their evolution altered depending on the evolution of the primary star. If the primary BSG evolves into a black hole, then this could alter or even destroy the companion star if it were to cross the event horizon.

Out of the sample collection of stars from tables 1-3, there are no stars near enough to cause a devastating effect on the Earth, either from a supernova explosion or any effects from a black hole. To put into perspective, if the Sun were to hypothetically turn into a black hole, then the orbit of Earth would not be effected in any way. The only effect this would have on the Earth is a drop in temperature. Therefore black holes that are further away from the Earth will have no effect, even if they are massive black holes.

# 4. CONCLUSIONS

This project has looked at the formation and evolution of blue supergiant stars, some of the processes that occur within and around these stars as well as some situations in which the evolution of BSGs could be heavily impacted. In section 3.1 the discussion started with the formation of BSGs which can be generalised into a four-step process. The first thing to note about star formation is that it occurs in large clouds of gas known as nebulae. Within nebulae, pockets of compressed gas form and later leads to protostars being formed. This can then cause material to be gravitationally bound to the protostars and then a combination of turbulent and pressurized clouds allow material to be available in the cores during the start of high mass star formation. Then forces either from the core or from an external source, potentially a shockwave from a supernova, cause an inflow of mechanical energy to balance gravitational forces and turbulence.

There are theories that the next step, the collapse phase, occurs at this point in certain parts of the nebula whilst other parts continue with the compression phase. This introduced two theories named the monolithic collapse theory and the competitive accretion theory. The former assumes that the compression phase is a transient phase caused by the random motions of material within the nebula and that the final mass of the star being produced is linked with the initial mass needed for the formation process to begin. Whereas the latter states that material can come from multiple sources in the nebula to make up the star material and also that multiple protostars are formed at the same time leading to a competition to accrete mass.

Once the collapse phase begins, which occurs when gravitational forces dominate over the other combined forces and cause the collapse of the protostar to form a star. There is a correlation that denser parts of the system collapse faster than the less dense parts of the system leading to a non-homogeneous collapse. Various forces play roles in the collapse and consequences arise from conservation of angular momentum such as accretion disks forming, and centrifugal forces increase. The accretion phase when mass starts to enter the core of the protostar via material travelling along the accretion disk and the star starts to gain mass. Eventually the disruption phase occurs in which the outer layers of the accretion disk, which are further away from the inner layers, are not gravitationally bound and so expands and escapes from the star. The rest of the accretion disk undergoes photoevaporation and the star is born. Therefore objective 1 has been accomplished

During the main sequence phase the star undergoes nuclear fusion in the core in the form of the CNO cycle. This is the net reaction of 4 hydrogen particles reacting with Oxygen, Carbon and Nitrogen to produce alpha particles and energy. As fuel runs out in each nuclear fusion process the core contracts, increases in temperature and density, which then allows the next fusion reaction to occur. As heavier elements are produced and this fuel runs out, the core keeps contracting and the star eventually fuses iron which absorbs energy and starts the inevitable process of the star’s death.

During their lifetimes, BSGs experience a characteristic stellar wind caused by radiation pressure generated in the core. The stellar wind causes an outflow of material out of the star and consequently over time causes the star to lose mass. Through observations, measurements, and calculations using equations, O and B type stars lose between one millionth and around one billionth of a solar mass per year. This shows that some BSGs would lose the equivalent mass of the sun after around one million years and others would lose the same mass over a longer period of time. These results imply that for a substantial amount of mass to be lost the star would have to exist for a longer time than the star’s maximum lifetime.

Being in a binary system could also heavily impact the evolution of a BSG if mass transfer occurs frequently enough and with enough intensity to cause a substantial amount of mass to be lost form the BSGs. This could occur if the companion to the primary BSG is a black hole, neutron star or celestial body of similar gravitational force. A large fraction of O and B type have been found to be in a binary system suggesting that the reported mass loss rates from observations already considers potential mass transfer episodes between the primary BSG and its companion star. If the companion star outlives the BSG primary star, then it could be seen that the companion star will either be heavily affected by the supernova explosion of the BSG whether it be destructive or constructive in effect. This could lead to the companion star gaining material and over a long period of time form a new binary system with the original companion star becoming the new primary star.

Several studies have been carried out (MiMeS and BOB) to analyse magnetic fields of O and B type stars. Both studies found that magnetic fields of such stars are dipolar in characteristics, range from a few hundred Gauss to a few ten thousand Gauss and are structurally simpler than those fields found in stellar mass stars such as the Sun. They are generally stronger than stellar mass magnetic fields, and around 7% of observed stars were found to host a detectable field. It has also been stated that this area has had no impactful change in the last decade meaning that current technology is a limitation. Future technology would need to be more sensitive and would require filters that can detect weaker magnetic fields. Magnetic processes such as stellar spots and stellar flares are theoretically possible for BSGs to experience through dynamo action and turbulence in convective regions just below the surface of the star. The study of all of these properties of magnetism, fusion and composition means that objective 3 has been accomplished

The final evolutionary stages of BSGs are a result of catastrophic collapse of the star in the form of supernovae. A huge release of energy that sends shockwaves through vast distances in the interstellar medium, potentially affecting the formation of other stars. The stellar remnants then form either a neutron star or a black hole depending on the mass of the core. If there is more than 3 solar masses left in the core, then gravitational forces will dominate and forma singularity and then a black hole will be formed. If there is less than 3 solar masses in the core, then a neutron star will form and continue to exist for long periods of time. Thus objective 2 has been accomplished

Stars have existed in the universe for the majority of its lifetime, around 13 billion years, and each star can shape the evolution of the universe. Especially high mass stars which evolve into phenomena such as black holes and neutron stars that have extreme forces and last for exceptionally long periods of time. BSGs also encompass a large amount of binary systems which could lead to an understanding of how these systems alter stellar evolution of both stars involved as well as why the majority of BSGs are in binary systems.

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# 6. LAY SUMMARY

Blue supergiant stars (BSGs) were one of the first generation of stars that came into existence several hundred million years after the big bang. They were responsible for lighting up the dark early universe. Their lives and deaths led to the formation and distribution of important heavy elements that would assist the next generation of stars and lead to the formation of galaxies and planets as well as alter the evolution of the universe.

The fundamental properties of BSGs include very high mass, at least around 14 times more massive than the sun and some being up to 50 times more massive, they are of O or B star type meaning that they also have very high temperatures and luminosity values. Due to their high temperatures, they burn with a bright blue glow and therefore produce large quantities of UV photons. I aimed to explore and research the general formation, evolution and death of BSGs, processes that occur within these stars and any situations that alter these processes.

Formation of BSGs are similar to most stars with the main differences being faster formation, higher density of hydrogen in the star forming nebulae and different forces playing key roles in high mas star formation. The main difference between high mass stars and a star like the Sun is that high mass stars will continue to gain mass as it evolves through the main part of its life. Whereas smaller mass stars will obtain all of the mass that it will have in its entire lifetime before it stars to evolve through its main part of its life. During formation it is possible for more than one star to form which can lead to a binary system to develop, a system of two or more stars orbiting each other. If a BSG is located in a binary system, then this could theoretically impact how the star evolves.

BSGs are fuelled by a process known as nuclear fusion which occurs in the cores of all stars and involves hydrogen atoms fusing together to form helium and produce energy. Nuclear fusion differs in higher mass stars due to higher temperatures making more processes available. Fusion in BSGs involves hydrogen reacting with heavy elements like carbon, nitrogen and oxygen to produce helium, energy and radiation pressure leading to a balance of forces and prevents the star from collapsing under gravity.

BSGs have a characteristic stellar wind caused by an outflow of the outward flowing radiation pressure generated in the interior and material is blown out of the star at high speeds up to a few thousand km s-1 which over long periods of time could lead to the star losing large amounts of mass. On average BSGs will lose around 5 times the mass of the Sun over their lifetimes, this number could be affected by the star being in a binary system or if the star has fast or slow stellar winds. Overall the amount of mass lost through this process is not significant due to BSGs having much higher mass values than that of the Sun.

It was also discovered O and B type stars can host magnetic fields that are overall stronger than the fields of smaller stars such as the Sun. This leads to theories that question whether or not high mass stars can experience magnetic phenomenon such as stellar spots and stellar flares. Scientific surveys provide strong evidence to support this theory. When combined with other theories, this evidence strongly suggests that it is possible for stellar spots to occur on the surface of high mass stars. This therefore suggests that stellar flares can occur through magnetic field interaction with the stellar spots and further suggest that high mass stars can experience magnetic phenomena similar to the Sun.

It was stated that there has been no change in physical characteristics of magnetism in massive stars across1.5 decades [28]. It is therefore shown that more advanced technology would need to be developed in order to further research magnetic characteristics and properties in the future. This could lead to a better understanding of the evolution of high mass stars and processes that occur within them.

When BSGs near the end of their lives around 10 million years after their formation, compared to around 10 billion years for the Sun, gravitational forces dominate and the core experiences extreme pressure. The core then sends a shockwave outwards from the core and this leads to an explosion known as a supernova. The energy released during this explosion can be as much as the energy that Sun will produced over its lifetime.

High mass stars are an important area of research as their star types were one of the first generations of stars shortly after the big bang. Having a fundamental understanding of how high mass stars form, evolve and die, as well as the processes that occur within and around these stars could lead to a fundamental understanding of the early universe, how it evolved from the so-called dark age to the present universe that we observe today. Understanding the effects of the interactions of high mass star death on the surrounding galaxies and stars could also lead to an understanding of the formation of other types of stars and the formation of galaxies. The study of BSGs is a useful study into very distant stars as they are some of the brightest stars in the universe and so can be seen from much further away than other types of stars making them easier to study than other star types of similar distances away from Earth.